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Research Article

Speed Control of Brushless Dc Motor Using Current Fed Quasi Z-source Inverter with Regeneration Capability

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Abstract: Current fed Quasi Z-Source Inverters (qZSI) have the advantages of voltage buck-boost capability, improved reliability, reduced passive component ratings, continuous input current, a common dc rail between source and inverter and unique regeneration capability. This current-fed qZSIs are bidirectional with an additional diode, unlike the voltage-fed ZSI that needs a switch to achieve bidirectional power flow. Since current fed quasi Z Source Inverter has many advantages it can be employed for motor drive applications such as Brushless DC motor (BLDC) drive. Therefore this study proposes the use of qZSI for BLDC motor. The simulation results for the same are presented in this study.

Keywords: BLDC drive, qZSI, Z-source inverter

INTRODUCTION

Shuitao *et al*. (2011) introduced Z Source Inverter and discussed the limitations and barriers of VSI and CSI such as they are not having buck-boost capability together, their circuits are not interchangeable and they are vulnerable to Electromagnetic Interference (EMI) noise. He presented a ZSI and its control method for implementing dc to ac, ac to dc, ac to ac and dc to dc power conversion. The Z-Source converter employs a unique impedance network (or circuit) to couple the converter main circuit to the power source in a single stage. A controller was designed for three level voltage source inverter for induction motor application (Pandian and Rama Reddy, 2009). Z-source rectifier/inverter system can produce an output voltage greater than the ac input voltage (for rectification) by controlling the boost factor, which is impossible in traditional Adjustable Speed Drive (ASD) systems. A Z-source inverter for ASD was proposed in Qin *et al*. (2009, 2011). The VSI based ASD suffers from the drawbacks of low output voltage, voltage sags and lack of ride through capability for sensitive loads. This study states that the bidirectional power flow required for drive applications can only be achieved in a ZSI by replacing the diode with a bidirectional conducting unidirectional blocking switch. In that case, the advantages of single-stage topology are missing. Shoot through duty cycle control for voltage boost up operation and operating modes of ZSI such as active state, open zero state and shoot through state were also analyzed. The ZSI minimizes the motor ratings to deliver the required power and reduces in-rush and harmonic currents (Qin *et al*., 2011).

Qin *et al*. (2010) designed and developed a 50 kW, Z-Source Inverter for Fuel Cell Vehicles with maximum boost control method, which gives the highest boost ratio and lowest voltage stress across the switches and it is also useful for high frequency operation or constant speed operation. Hence for a variable speed drive system, maximum constant boost control has been chosen. A dc rail clamp circuit has been used so as to reduce the overshoot of the device during turn off. Peng (2003) proposed and presented the design of bidirectional ZSI for electrical vehicles. The ZSI work in DCM Discontinuous Conduction Mode (DCM), therefore the output voltage will be uncontrollable and the system becomes unstable. To overcome this limitation a Bidirectional ZSI topology was proposed. By using this topology, the inverter was able to completely avoid the unwanted operating modes by turning on the switch during all active states and traditional zero states. In addition to that it provides the circuit a bi-directional power flow. A current fed quasi ZSI for hybrid electric vehicle was developed in Fang *et al*. (2005). The current-fed qZSI is very promising for use in hybrid vehicles because of the following unique features such as buck/boost voltage capability in single stage configure ration which means no need for any dc-dc converters to control the battery state of charge, or boost the dc bus voltage. It has greater reliability because the open zero states can no longer destroy the inverter due to the quasi-Z network. The performance of ZSI for Permanent Magnet Brushless Motor was presented in Miaosen *et al*. (2006) in which the voltage stress of ZSI supply exceeds the DC-DC Boost Inverter (DBI) supply. Husodo *et al*. (2010) and Giuseppe *et al*. (2009) presented the Analysis and

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Simulations of ZSI Control Methods in which Simple boost control method gives independent relation between modulation index and shoot-through duty ratio. The selection of high modulation index and shoot-through duty ratio can reduce the inverter's dc link voltage overshoot and increasing power delivery capacity of the inverter which is termed as Simple Boost control. Selection of constant value of shoot through duty ratio in all modulation period results in reduced passive component rating and selecting a lower value of shoot through duty ratio reduces the voltage stress which is termed as maximum constant boost control.

Husodo *et al*. (2010) presented a Current-Fed QZSI with Voltage Buck-Boost and regeneration Capability. The Current fed quasi Z-Source Inverter replaces the two stages of bidirectional DC-DC converter and conventional pulse width modulation inverter to control the power of the motor and the state of charge of the battery in hybrid vehicles in single stage configure ration. Qin *et al*. (2011) presented the discontinuous operation modes of current fed quasi Z source inverter. The Current fed qZSI has lower current stress on inductor compared to current-fed ZSI. The analysis and control methods proposed in Fang *et al*. (2005) are based on the assumptions that the capacitor voltage is almost constant and equal to the input voltage. These assumptions become invalid when the capacitor is very small or the load power factor is low in some applications that the volume is a very crucial factor. The capacitor voltage has high ripple or even becomes discontinuous. In these cases, the circuit has two new operation modes except for the normal three modes, which is called discontinuous operation modes. This study analyzed the characteristics of the discontinuous operation modes and derived the critical conditions for these new modes under different control strategies.

MATERIALS AND METHODS

Circuit description: The proposed circuit is shown in Fig. 1. Current fed qZSI feeds the inverter. The inverter supplies stator winding of a BLDC machine. The PWM pulses for inverter are generated based on the signals obtained from Hall sensors of a BLDC motor. The motor specifications are as follows:

Rated Voltage -160 V
Power -373 W
Resistance (Per phase) -0.7 Ω
Inductance (Phase-Phase) -2.72 mH
Speed constant 18.62 rpm/volt
Torque constant -0.049 nm/A
Number of poles -4
Rated speed -4000 rpm
Rated current -17.35 A
Moment of Inertia -0.0002 g-cm^2

Governing equations of current FED QZSI: Direct voltages and currents are involved in the Z network. The impedance link delivers a current that is assumed to be constant in each mode. Id is the current drawn from the Z-link by the load. Dop is the open zero duty ratio.

Ipn Current fed to the inverter bridge = 20A = Z link current.

Iin Input current of the current fed QZSI:

$$Ipn = Iin + (2 * Il) \tag{1}$$

$$Ipn = \left(\frac{1}{1-Dop}\right) * Iin$$

$$Ipn = B * Iin \tag{2}$$

Relation between output peak ac current and Z link current:

$$\text{Peak ac current } i = \left(\frac{\sqrt{3}}{2}\right) * m * Ipn \tag{3}$$

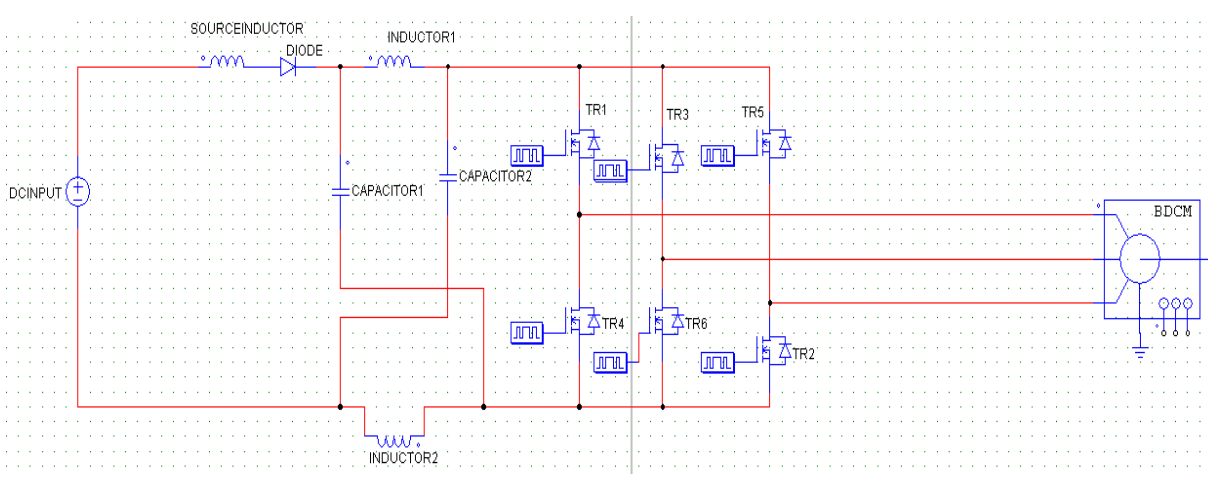

Fig. 1: Quasi-ZSI fed BLDC motor drive

Rms value of ac current $Io_{(rms)} = i/\sqrt{2}$ (4)

Inverter gain $G = i / \left(\left(\frac{\sqrt{3}}{2}\right) * I_{in}\right)$ (5)

Inverter gain $G = \frac{1}{1-2*Dop} * m$ (6)

Let $B = 1/(1 - 2Dop)$

$Il3 = P/Vin$

The current stress of the switch is equal to the current at pn is:

$Is = Ipn$ (7)

$Ipn = \frac{1}{1-2*Dop} * Iin = B * Iin$

Capacitor voltage increases in open zero state. So the peak to peak value of voltage ripple is:

$\Delta Vc = \frac{ic*Top}{C} = (Iin + Il) * Top$ (8)

where, $Top = Dop * Ts$.
To have continuous mode of operation:

$Vc\ ((_{min}) = Vin - (\frac{\Delta Vc}{2})$
$= (P/Iin) - ((1 - Dop)/(1 - 2Dop) * (I_{in}) * (Top/(2 * C))$ (9)

Assume the load impedance is Z. From the power balance, the input power can be calculated by output current as:

$P = \left(\frac{3}{2}\right) * Z * cos\emptyset * (i^2)$ (10)

Design spécifications:

DC input voltage: 48 V
Source inductor: 2 mH
Switching frequency -20 kHz; $Tsw = 1/f_{sw} = 50$ µsec
Peak to Peak ac output voltage +30 to -30 V
Output power of the converter = 600 W
Voltage rating of the converter = 30 V
Current rating of converter = 20 A
AC output frequency = 50 Hz
Inverter gain G = B*M = 1.9 = 2 (approximately)

In current fed qZSI to have continuous mode of operation, Vc should be 48 V:

$L_1 = L_2 = L > \frac{ds*Tsw*Vc}{(Inductor\ ripple\ current)} = 2.5$ mH (11)

$C_1 = C_2 = C = \frac{(Iavg*Tsw*ds)}{(0.03*Vc)}$ assuming a 3% ripple in capacitor voltage =100 uF (12)

SIMULATION RESULTS

The Simulation Circuit shown in Fig. 2 is for six pulse operation using position sensor feedback. As BLDC motors are electronically commutated rotor position information is needed for proper commutation. Commutation refers to the sequence of energizing stator coils for proper rotation of motor. This position information is provided by three Hall Effect sensors. The switching pulses are shown in Fig. 3. The input DC

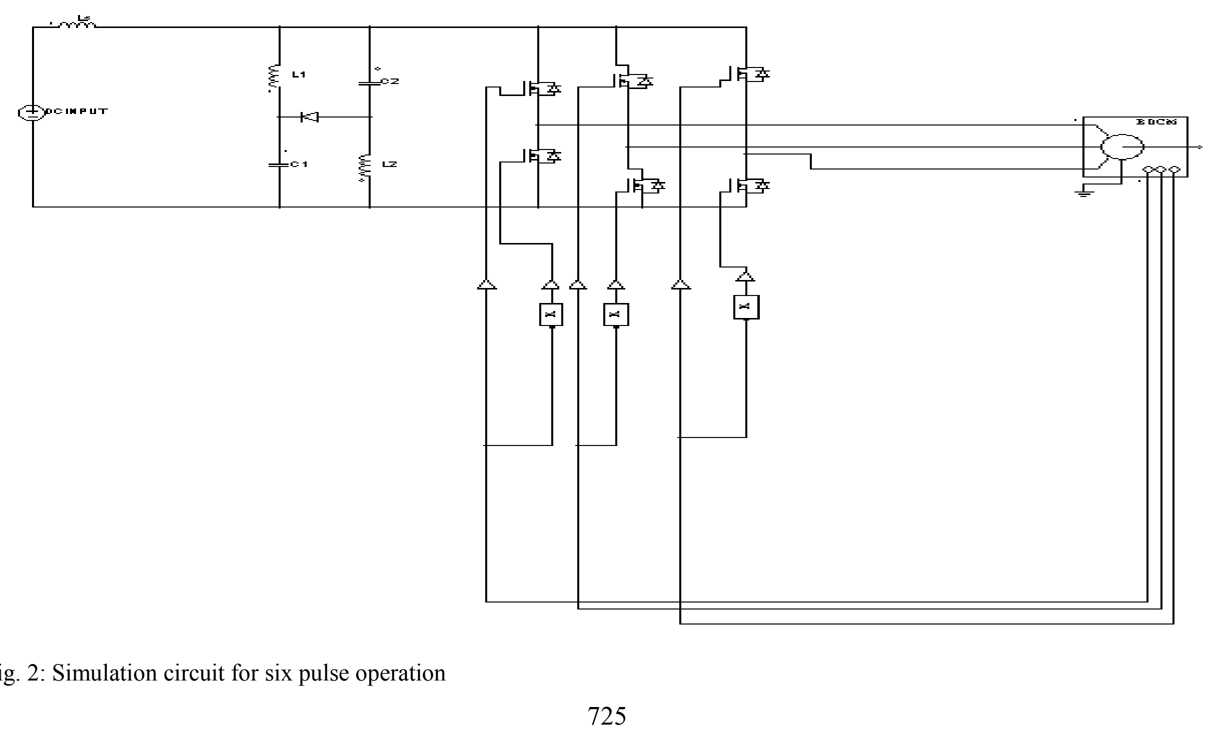

Fig. 2: Simulation circuit for six pulse operation

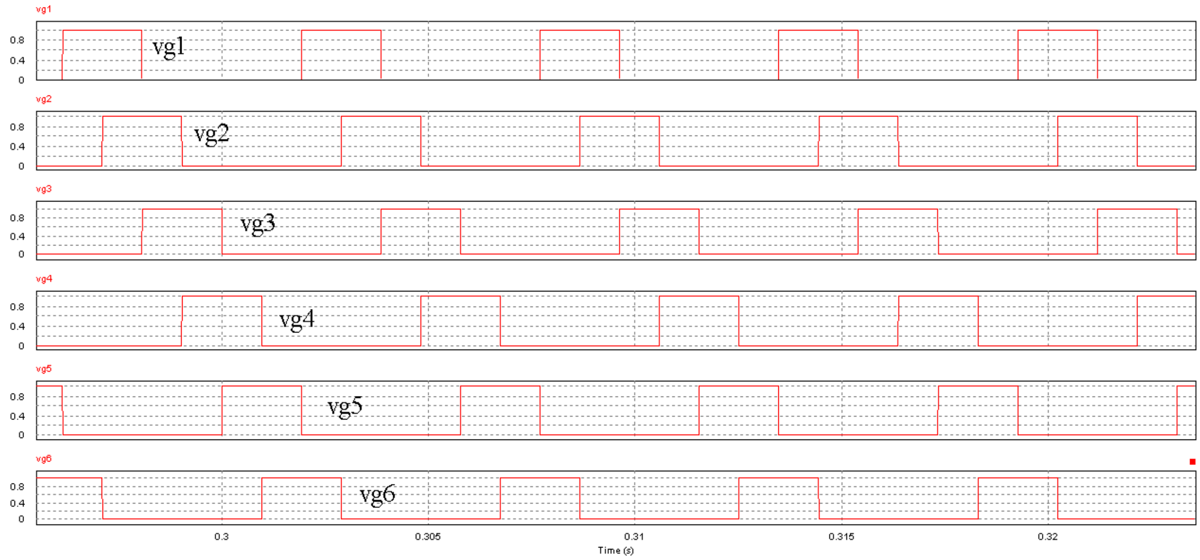

Fig. 3: Sequence of gating pulses

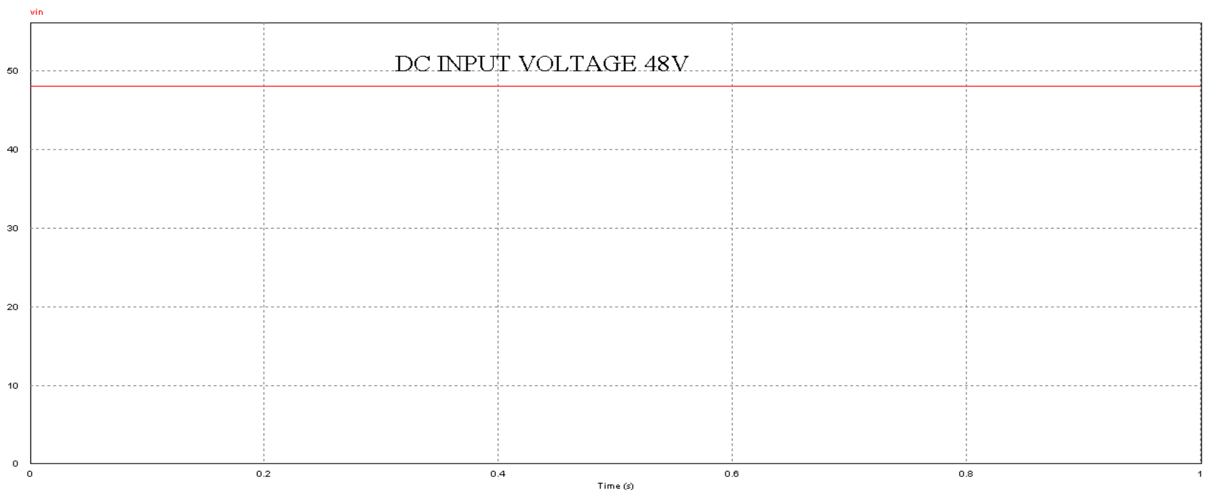

Fig. 4: DC input voltage

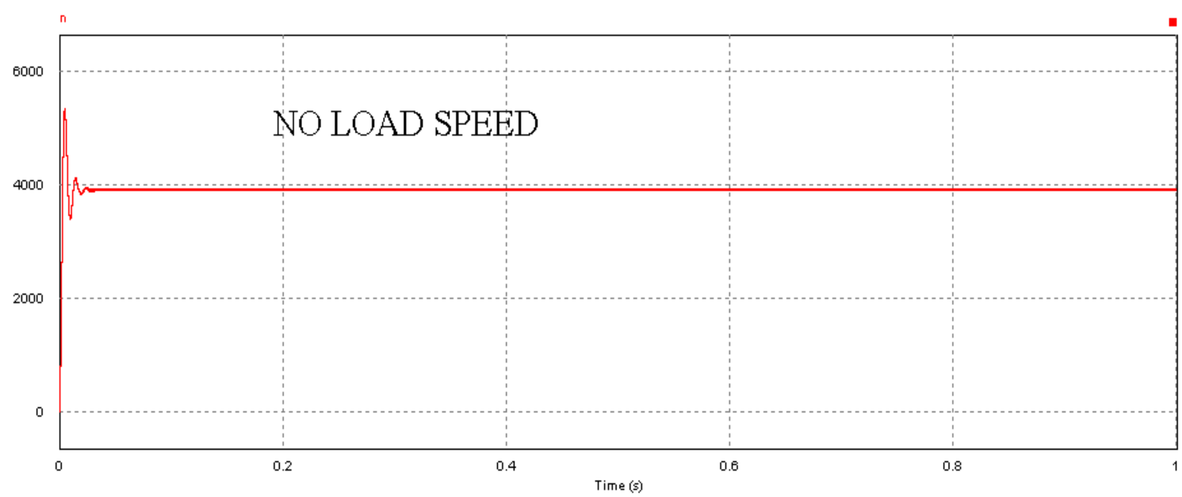

Fig. 5: No load speed

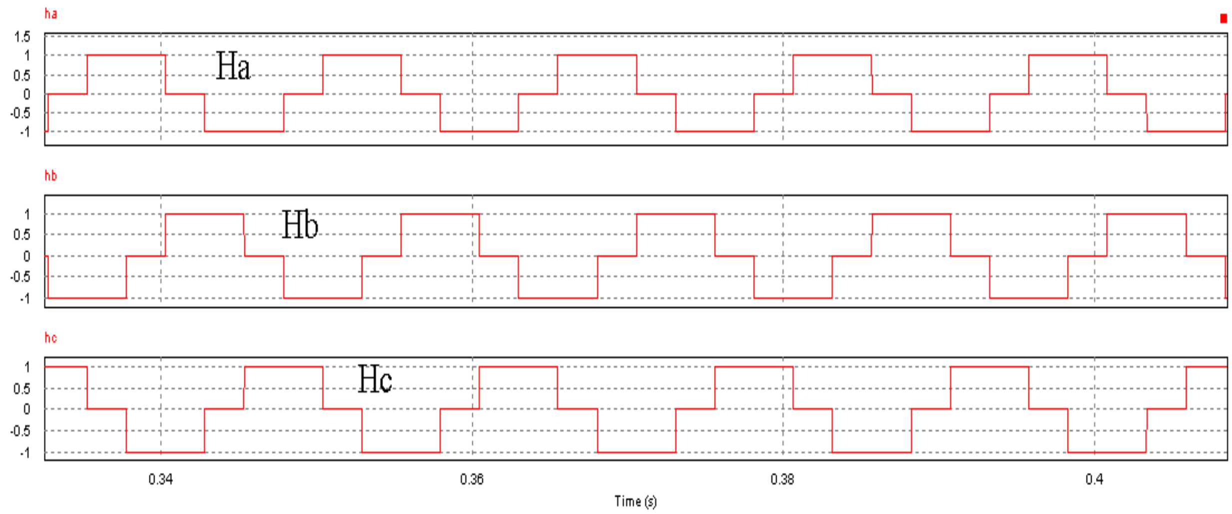

Fig. 6: Hall sensor output

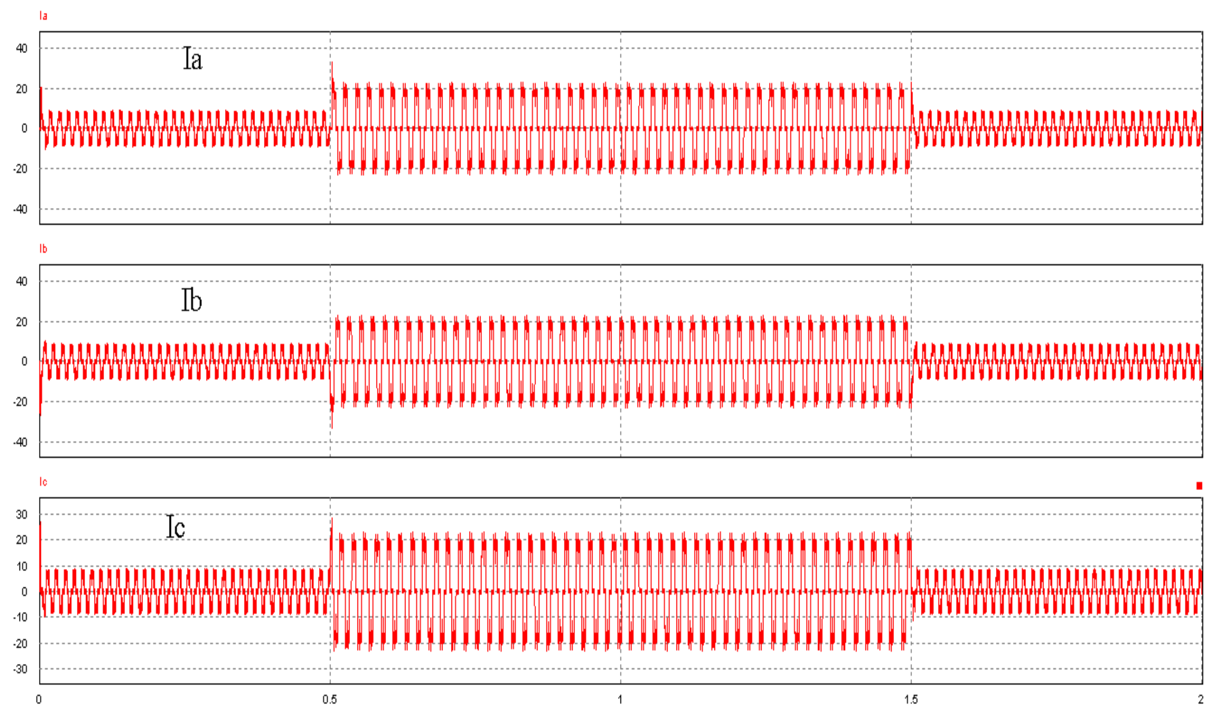

Fig. 7: Stator line currents during no load and load conditions

voltage to the current fed qZSI is 48 V to produce an output voltage of 30 V (line-line) rms using PWM duty cycle control. This dc input voltage is shown in Fig. 4. The no load speed is shown in Fig. 5. Rotor position information needed for commutation purpose is provided by three Hall Effect sensors. A Hall Effect sensor is a type of position sensor that provides three pulses depending on the rotor shaft position. The three logic signal output pulses A, B and C are spaced 120^0 apart. The Hall Effect sensor output is shown in Fig. 6 and Table 1.

Table 1: Simulation specifications

Parameter name	Simulation parameter	Value
DC input voltage	DC input	48 V
Source inductor	Ls	2 mH
Z link inductors	L1 and L2	2 and 2 mH
Z link capacitors	C1 and C2	100 and 100 μH
Z link voltage	Vz link	48 V
Stator line currents	Ia, Ib and Ic	20 A
Stator line voltages (RMS)	Vab, Vbc and Vca	30 V

During load conditions the motor draws more current with increase in torque and reduce in speed as voltage drops to drive the load. As BLDC motors are

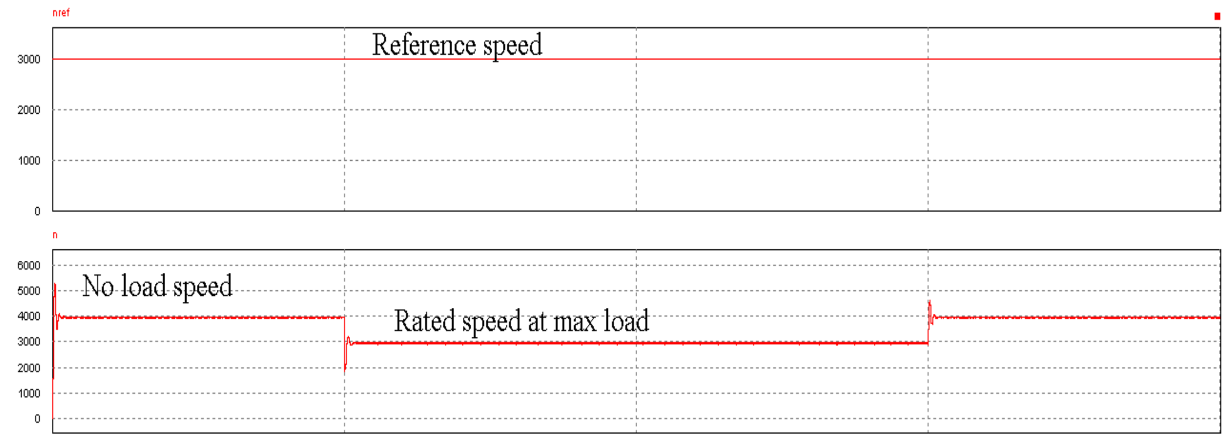

Fig. 8: Speed waveforms

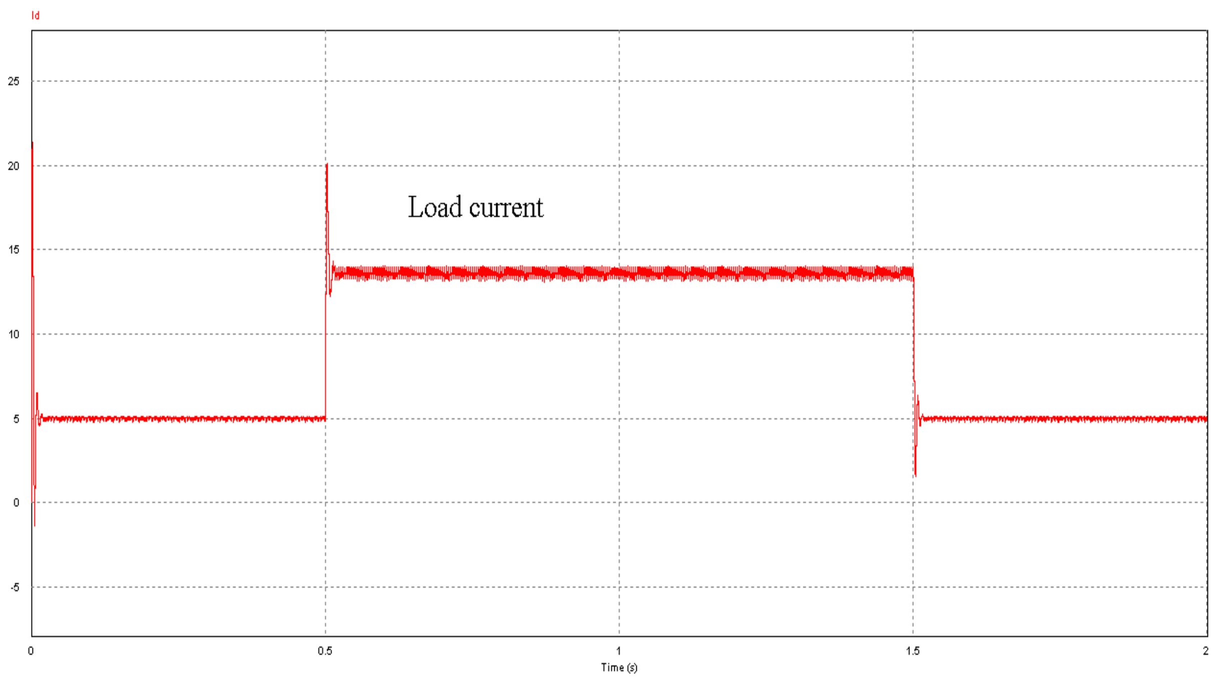

Fig. 9: Load current waveform

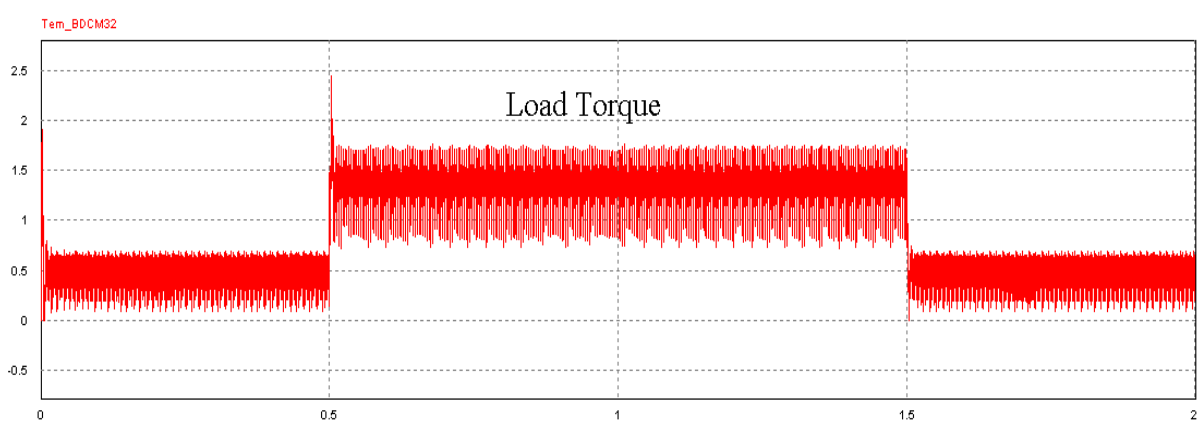

Fig. 10: Load torque waveform

generally star connected the line current and phase currents are of same value of square wave pattern. Here load is connected from 0.5 to 1.5 sec for a total duration of 2 sec. The change in stator line currents during no load and load conditions are shown in Fig. 7.

The speed variation during load change is shown in Fig. 8.

As BLDC motors mimic the characteristics of DC shunt motor the torque is directly proportional to stator armature current. The motor is driving a load which draws a current of nearly 13A from motor. Here load is connected from 0.5 to 1.5 sec. The increased load current and load torque is shown in Fig. 9 and 10 respectively.

CONCLUSION

A current fed qZSI having for a BLDC motor was designed. From the simulation results it is observed that due to the presence of energy storage elements in the Z link it is possible to get voltage buck/boost capability and inversion in single stage configuration. From the simulation results it is also observed that the qZSI supports BLDC for variable speed/torque operation. But the ripple content in torque is high; therefore the research can be further focused on reducing the torque ripple.

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